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A Novel Composite Material for Foldable Building Envelopes

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Abstract: Contemporary research is increasingly focused on studying buildings that either interact with environmental boundaries or adapt themselves to their users' needs. In the current literature, this kind of ability is given different names: responsivity, adaptability, smartness. These are different ways to refer to a common concept, with subtle nuances. Foldable surfaces are one of the most interesting geometries able to give responsivity to building components, but often their production is complex and expensive. The aim of this research was the creation of a novel material that can provide lightweight solutions for foldable building envelopes. This composite material can be folded and unfolded easily, like a sheet of paper, but with a higher mechanical performance. It is made with the thermoplastic elastomer SEBS (styrene–ethylene–butylene–styrene) as its matrix, as well as a fabric reinforcement. In this paper, following an introduction to this subject, the authors present the composite material's production methods and its mechanical characterization.

Keywords: textile architecture; fabric structures; origami; composite material; responsive surface

1. Introduction

At present, it is difficult to give a fixed structure to the functions carried out inside buildings via hierarchical organization and a rhythmic arrangement of spaces, because of their transitory nature. Functions tend to be ever-changing due to the contemporary lifestyle, with a consequent variability of lighting and thermal needs. The necessity of the ability to change shape is a direct consequence of this consideration. The kinematics may involve either the entire building including its structure—especially in temporary pavilions or small buildings [1]—or only certain building components [2]. In the latter case, kinematics generally involves the envelope, which is the main interface between the building and its surrounding environment. Via the kinematic mechanism of the envelope, one can adjust the solar radiation and illumination [3–6], ventilation, or acoustic behavior [7,8]. Over time, the need for kinematic mechanisms for the control of different configurations has resulted in the introduction of a system of actuators in building components (one very common application is roller shutter controllers). The electrification of actuators and the consequent introduction of a system of sensors and a control unit have led to a complete automation of the kinematic mechanisms as a result of certain inputs which give rise to the so-called adaptive or responsive buildings [9,10].

In the context of a broader definition of convertible architectural components, Frei Otto investigates the types of motion used to confer such properties [11]. The most used in recent architectural projects is folding [12]. Its advantages, thanks to the properties generated by a fold on a surface, are dual. In fact, on the one hand, folds work as hinges which generate a possible rotation around the axis of the fold [13]. On the other hand, they cause an increase in mechanical properties thanks to the so-called "form-resistance" acquired by the surface [14]. To create and control the different folding patterns that can be given to a surface, an appropriate reference is the oriental art of origami, which is based on two different types of folds: first fold and reverse fold [15]. Today the attempt to exploit the properties of origami surfaces is encountering growing success in the various branches of engineering, especially in combination with Smart Materials [16]. This research clearly shows that the use of folding surfaces offers a high potential for future research, due to their mechanical and kinetic properties.

In this field, the most recent research focuses on passive systems based on an intrinsic control, characterized as such in [5], in opposition to active systems based on extrinsic control via the use of sensors and actuators which need external energy resources. Passive systems are distinguished by their ability to self-adapt in response to certain inputs when using Smart Materials [17]. These components perform highly in terms of management; they do not require mechanical actuators, nor sensor and control systems. Conversely, however, they do not guarantee an individual control by users for their specific requirements, and this characteristic is usually not appreciated [3]. The wide variety of interpretations of this theme is reflected in the diversification of definitions (e.g., adaptive, responsive, convertible, etc.) that are closely linked with individual studies on the subject and are typically varied depending on the degree of automation integrated into the component [18].

This article shows the results of experimental tests for the production of an innovative and lightweight material that is suitable for use as an architectural component with an integrated kinematic mechanism. The aim was to obtain an easily controllable material, like a sheet of paper which, when folded, can rotate easily around the axis defined by the fold.

2. Materials

2.1. State of the Art

Contemporary approaches to the issue of the responsiveness of architectural components tend to simplify the moving parts as much as possible, avoiding the use of complex mechanisms. This is essentially due to a need for simplification of their management. Mechanical systems, even high-quality ones, require maintenance plans and operations. These are often not carried out, due to negligence or high costs, thus causing the premature decay of component performances. Elastic kinematics [3,19] is an alternative solution. This system is based on the use of materials which are capable of undergoing a deformation, storing energy, and returning to the initial position when no longer stressed. Thanks to the absence of hinges, this entails a much lower need for maintenance cycles than mechanical systems, and is therefore more economically sustainable.

In recent innovative architectural designs, the elastic kinematics of components is obtained using composite materials such as glass-fiber-reinforced polymers (GFRPs). These were used for the construction of the Thematic Pavilion sunblind at the EXPO 2012 in Yeosu and for the Flectofold prototype made at the Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart (Figure 1a). The latter was inspired by the deformation mechanism of the *Strelitzia reginae* flower. This flower has anthers made of two closed petals to protect the pollen. When a bird rests on these elements, the flexional deformation of the anther determines a rotation of the petals and the opening of the system that releases the pollen onto the bird's body. When the bird moves away, the system's elasticity reverses the deformation and closes the two petals. This movement inspired a component made of a fiber-reinforced polymer (FRP). This material has an advantage over traditional materials used in the construction industry, such as steel or aluminum, thanks to its high elastic deformation due to its reduced rigidity–resistance ratio. In particular, the material used is made of a fiberglass fabric with a plain weave and weighs 80 g/m^2. Tissue layers vary from four to eight depending on the distribution of stresses on the surface. The composite matrix is made of ultra-flexible epoxy resin. The production process is the Vacuum Assisted Process (VAP). The backbone of the component is a profile produced with a pultrusion process and is bound with the lateral "wings" forming an L-shaped (single-wing) or U-shaped (double-winged) system. This profile is made of GFRP oriented in the direction of longitudinal stresses. The main application of the component is in façade solar shadings where a system of actuators generates the flexion of the central spine of the component which, in turn, determines the opening of the two lateral lamellae [19,20].

The Hylite® panel is also made of composite material, consisting of a double layer of aluminum and a layer of interposed polypropylene (Figure 1b). If parallel grooves are milled into both external aluminum surfaces, this panel can be used for folding components. The company guarantees the possibility of performing more than 80,000 closing cycles. These properties have stimulated research into possible applications for deployable shelters [21].

Growing attention to foldable components stimulates research not only into innovative composite materials but also into innovative manufacturing processes of traditional materials such as wood. These innovative processes make it possible to obtain components with kinematics linked to the elastic deformation. For instance, using a repetitive 2D cutting system managed by a computer numerical control (CNC) cutter, it is possible to obtain a repetitive pattern material (RPM). These materials are endowed with an elasticity that the constituent base material does not possess (Figure 1c), but which derives from the cutting geometry [22].

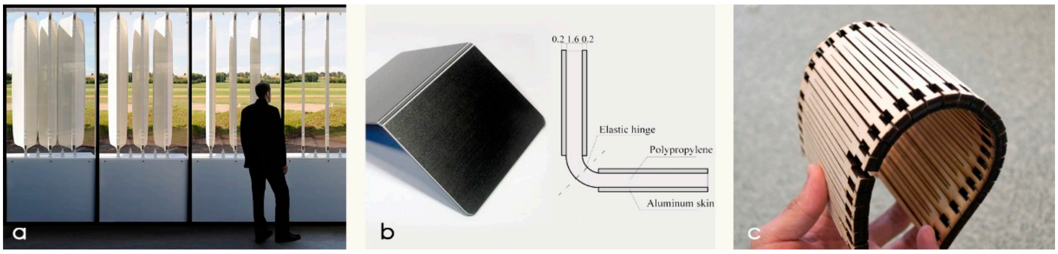


Figure 1. (**a**) Flectofold prototype photo by Julian Lienhard; (**b**) Hylite® panel photo by 3AComposites and Curletto and Gambarotta [21]; (**c**) Wooden repetitive pattern material photo by Ohshima et al. [22].

Among the numerous possible solutions, we attempted to supplant those using hinges with bending caused by the elastic deformation of a composite material, using fabrics as reinforcement and a thermoplastic elastomer (TPE) as matrix.

In recent decades, the use of composite materials in the building industry has rapidly increased, especially in the field of the so-called fabric structures [23] or textile architectures [24]. For these types of systems, the properties of the unique material used are decisive in achieving good performances, but the fabric architecture has widely diversified applications: from permanent to temporary structures, from fixed configurations to easily movable ones in relation to boundary conditions. Thus, the material's properties are based on building requirements. It should provide protection from rain and sun and, in relation to a specific project, be more or less transparent, water-vapor-permeable, penetrable by warmth, and so on. The material has to be lightweight, but also adaptable to specific requirements. A composite material meets this objective because it is manufactured with two or more components that together endow it with properties different from the separate basic ones. A composite is made with a reinforcement (discontinuous material that is the main contributor to the strength of the composite), and a matrix that fastens the reinforcement into position, transfers the forces acting on the material to the reinforcement, and also defines the surface finishing and resistance to ageing [25]. In addition, the ways matrix and reinforcement are combined during processing have different effects on the final component.

Composite materials for textile architectures are typically fabrics, either natural or synthetic, coated with polymers. The most commonly used fabrics have widely different characteristics: from a cheap material with a short lifespan (e.g., polyethylene terephthalate, PET), to a high-performance fiber such as Aramid or polytetrafluoroethylene (PTFE). The most used natural fiber is cotton, even though it has a short lifespan of only around four or five years. Hemp and flax are more sustainable, stronger, and more UV-resistant than cotton, although today they are rarely used [26].

2.2. Novel Composite Material

With these assumptions, fiber composite materials seem to be the best solution for origami surfaces. In fact, the idea is to preserve the typical characteristics of the fabric, such as light weight and a versatility similar to paper, while ensuring protection from the deterioration caused by atmospheric agents (rain, hail, sunlight, etc.). As mentioned above, this is ensured by the use of a polymer coating.

Our idea was to create a composite and then imprint a folding pattern into it post production. Once shaped, commonly used thermosetting polymers degrade if melted again. So, we used a TPE that withstands manipulation at high temperatures to guarantee the foldability of the composite. The two phases of production make it possible to customize the shape of the different components and different kinematic mechanisms. Thus, the base material—an industrially produced composite—could be configured with a specific folding pattern for each project (Figure 2). This way, it is possible to combine industrial production with craft, as is currently required in an increasingly pressing market.

Figure 2. The novel composite material application: (**a**) as second skin to refurbish an existing building; (**b**) as temporary pavilion envelope.

2.3. Matrix

We selected SEBS (styrene–ethylene–butylene–styrene) as the thermoplastic elastomer, provided in pellets (Figure 3). Pellets were extruded with a Collin Teach Line extruder with a flat head (E16T model) and cooling roller (CR72T model) to obtain a thin film to be used as the matrix (Figure 4). For the first tests, we used a thin film with a thickness of 500 µm, but to optimize the composite by reducing the proportion of the matrix, we produced a film with a thickness of 170 µm.

Figure 3. SEBS (styrene–ethylene–butylene–styrene) pellets.

Figure 4. Collin Teach Line extruder with flat head (E16T model).

2.4. Reinforcement

As reinforcement, we tested two types of fabric to obtain two composites for different fields of application. The first one (Figure 5a) was C-200/T, a plain-woven carbon fiber fabric with a thickness of 290 ± 44 µm and a weight of 190 g/m^2, supplied by Prochima, while the second (Figure 5b) was Biotex Flax 400 g/m^2 2 × 2 Twill, a flax fiber fabric with twill weave, a thickness of 450–800 µm, and a weight of 400 g/m^2, supplied by Composite Evolution.

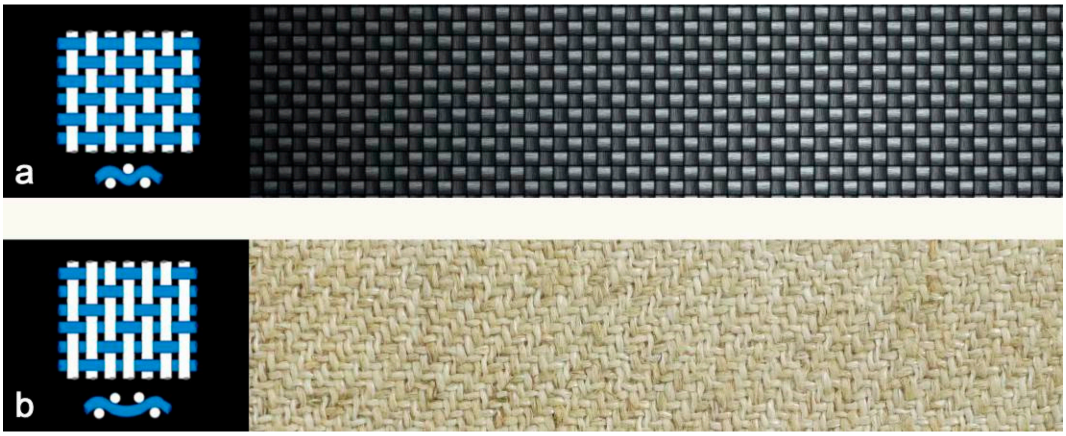


Figure 5. (**a**) Carbon fiber fabric; (**b**) Biotex fabric.

Flax has a low environmental impact and a low cost. However, it has a shorter lifetime and lower mechanical performance than other fabrics used for textile architectures, thus limiting its scope [27,28]. Using carbon fiber as reinforcement, we obtained a high-performance composite, suitable for applications in which high mechanical performance and long life are required [29].

For these experiments, the fabrics had not been subjected to surface pretreatments to improve the interface, although these are recommended [27] (especially for natural fibers) in order to obtain reference materials and then to compare their implementations through subsequent experiments.

3. Methods

3.1. Composite Creation and Setting of Production Parameters

To obtain the composite material we used a planar hot press to thermoform a layer of thin SEBS film and fabric. The press used was type PM20, produced by Campana s.r.l. The different parameters for optimizing production through the thermoforming of the composite are:

- Matrix-reinforcement ratio;
- Pressure;
- Times.

These parameters were not defined a priori, but were identified through the first production tests of the material. The thermoforming temperature was set at 180 °C. This was sufficient to obtain a good interpenetration among the materials, but not so high as to cause SEBS degradation.

3.2. Preliminary Analyses and Optimization of Production Parameters

The specimens were subjected to preliminary analyses (visual, tactile, thickness, cross-section) that made it possible to optimize the production parameters. The specimens that passed these tests were subjected to cross-section analysis, to verify the interface between matrix and reinforcement.

3.2.1. Visual Analysis

The purpose of this analysis was to detect—through observation—any defects related to the production process which might compromise the functionality of the basic material.

The main defects found were:

- The presence of air bubbles;
- The delocalization of reinforcement fibers;
- Burning of the reinforcement.

3.2.2. Tactile Analysis

For a sensory control of the product, the surface of the composite was rubbed with the palm of the hand, to detect any perceptible presence of unevenness in thickness and consistency, which are clear indications of faulty production.

3.2.3. Thickness

The samples made were subjected to measurements with a micrometer, and at least five measurements were taken to verify the constancy of thickness as evidence of a proper composition and fusion of the matrix with the reinforcement.

3.2.4. Cross-Section Analysis

The sample was cut, and its section was observed under an electron microscope. The visual analysis of the section made it possible to verify whether the interpenetration between matrix and reinforcement was complete (Figure 6).

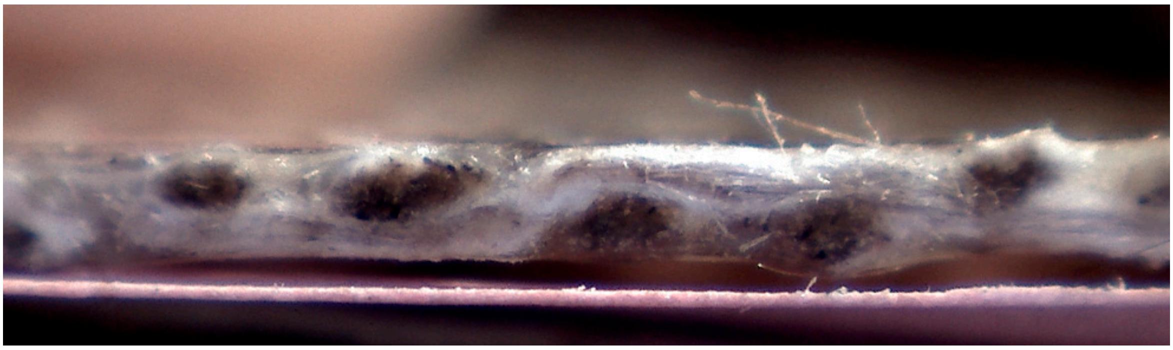


Figure 6. Cross section of SEBS–Biotex Composite.

3.3. Creation of the Folding Pattern

It is necessary to carry out a secondary thermoforming process to create a specific folding pattern on the composite material and, to do that, a mold must be made. The high costs for the construction of a professional metal mold led to the choice of an alternative route through rapid prototyping with the use of 3D printers. However, those available for experimentation work with polymeric materials which are not appropriate for molds for heated presses, since they are not good thermal conductors. Therefore, using the rapid prototyping method, we created a sort of disposable formwork to fill with a two-component epoxy resin and copper powder, in a weight ratio of 10:1. The mixture of the two elements was then used as a mold for the material.

3.4. Mechanical Characterization

The mechanical characterization of the tested composite materials consists of the determination of Young's modulus (E) and the shear modulus (G), as the basic data necessary to be able to undertake the study of the mechanical behavior of continuous surfaces made with such materials. To do this, two tests were chosen: a uniaxial tensile test on specimens with a reinforcement warp arranged parallel to the traction axis, and a bias extension test with a reinforcement warp arranged at 45° with respect to the traction axis.

3.4.1. Uniaxial Tensile Test

This test was an extensional test on a strip of the composite with a reinforcement warp oriented parallel to the axis of the specimen. It was carried out following the directives of the UNI EN ISO 527-4 standards. It prescribes the use of rectangular specimens of type 2 (without end tabs) or 3 (with end tabs) for composites reinforced with multidirectional continuous fibers, referring to the requirements of UNI EN ISO 527-1, point 5.1, for the choice. The specimens in SEBS–Biotex were made according to the indications of type 2, with L_3 = 200 mm, L = 150 mm, and b_1 = 25 mm (Figure 7a). Type 2 was satisfactory for the success of the test. Conversely, with the SEBS–Carbon specimens, even though they were made with the same geometry, tests were unsuccessful due to slipping. In such cases, UNI EN ISO 527-1, point 5.1, prescribes the use of type 3, rectangular but with ends tabs (Figure 7b). Therefore, it was decided to make PMMA (polymethylmethacrylate) beads glued to the composite. Different glues were tested, with the final choice falling on ethyl cyanoacrylate, which guaranteed the adhesion of the heel from the composite during tests.

The tests were performed with a Zwick-Roell z050 tabletop testing machine (Figure 8) with a 1 kN load cell for the SEBS–Biotex and 50 kN for the SEBS–Carbon, while the test speed was set at 2 mm/min. At least five tests were performed for each sample type.

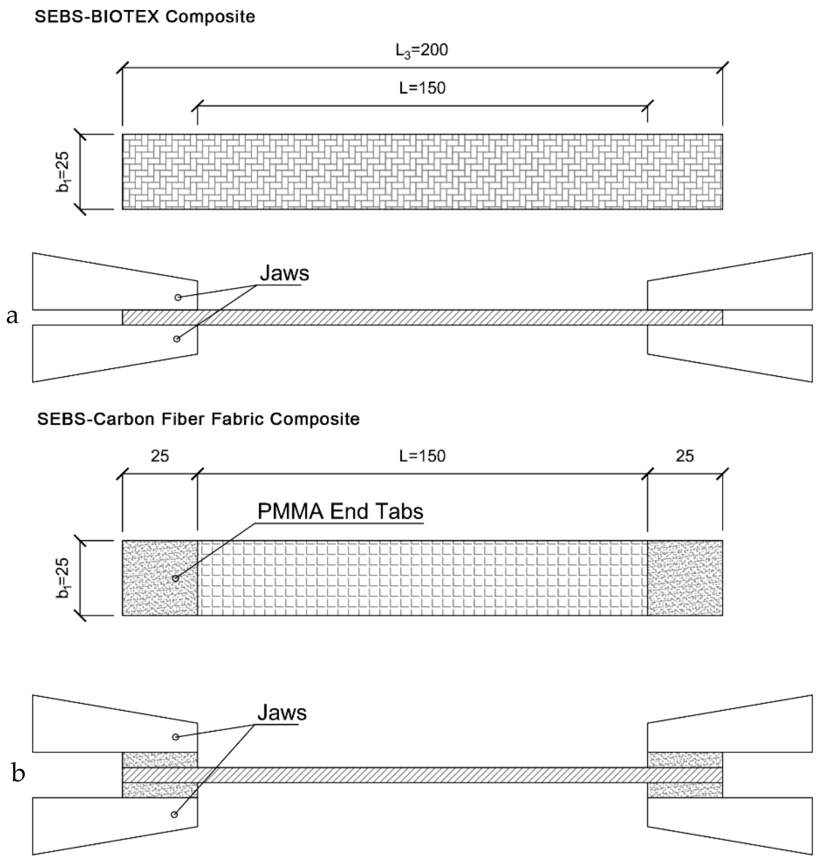


Figure 7. Uniaxial tensile test specimen dimensions. PMMA: polymethylmethacrylate. (**a**) SEBS-BIOTEX Composite (**b**) SEBS-Carbon Fiber Fabric Composite.

Figure 8. Zwick-Roell z050 tabletop testing machine.

3.4.2. Bias Extension Test

This was an extensional test on a strip of the composite with reinforcement warp fiber oriented at 45° with respect to the axis of the specimen. The tests were performed on rectangular samples of 150 × 50 mm^2 with a distance L_0 equal to 100 mm following the previously described regulation.

These samples were tested using a 2 kN load cell. The imposed speed was 3 mm/min and the pressure of jaws on the specimen was 30 N/m.

4. Results

4.1. Production Parameters

The optimization of the material production process (Tables 1 and 2) produced a composite in which the optimum matrix–reinforcement ratio was obtained using two layers of matrix with one interposed reinforcement layer. The optimization of the composite was accomplished by reducing the presence of the SEBS to a minimum, thus obtaining a composite as light and thin as possible.

Table 1. SEBS–Carbon fiber fabric composite.

Specimen	Layer		Weight (g)		Pressure (MPa)	Time of Pressure (s)	Thickness (mm)					Medium Thickness (mm)
	Matrix	Reinforcement	Matrix	Reinforcement								
S4C1_1	4 sheets of SEBS 0.5 mm	1 sheet of carbon fiber fabric	x	x	1	x	2.15	2.18	1.95	2.20	2.02	2.10
S4C1_2			x	x	2	x	1.95	1.83	2.07	2.10	1.93	1.98
S4C1_3			x	x	3	x	1.92	1.80	1.84	1.89	1.75	1.84
S4C1_4			x	x	4	x	1.82	1.72	1.70	1.72	1.60	1.71
note	_For a better control of the composite it is appropriate to record the weights of the materials before thermoforming them. _Minimize the thickness to optimize the performance of the material: more reinforcement and less matrix.											
S4C2_4	4 sheets of SEBS 0.5 mm	2 sheet of carbon fiber fabric	23.22	7.95	4	x	1.13	1.12	1.13	1.20	1.15	1.15
S4C2_6			22.82	7.22	6	x	0.94	0.97	1.03	1.08	1.00	1.00
S4C2_18			23.46	7.68	18	x	0.66	0.65	0.70	0.76	0.71	0.70
note	_The pressure time affects the result: it should be recorded.											
S4C2_20_90	4 sheets of SEBS 0.5 mm	2 sheet of carbon fiber fabric	23.36	6.95	20	90	0.65	0.66	0.61	0.66	0.64	0.64
S4C2_25_90			16.75	7.88	25	90	0.63	0.56	0.50	0.63	0.60	0.58
S3C2_5_60	3 sheets of SEBS 0.5 mm	2 sheet of carbon fiber fabric	16.54	5.78	5	60	0.62	0.60	0.64	0.63	0.68	0.58
S3C2_15_60					15	60						
S3C2_5_150			16.35	6.24	5	150						
S3C2_10_60					10	60						
S3C2_1_180					1	180						
S3C2_5_180			39.7	5.97	5	180						
S3C2_10_60					10	60						
note	_Testing with SEBS with lower surface development than fibers to try to reduce the amount of polymer. _SEBS "pulls the fibers" and dislocates it. does not reduce the thickness. Weak samples. _It is advisable to program other tests with SEBS and reinforcement of the same size.											
S3C2_2_90	3 sheets of SEBS 0.17 mm	2 sheet of carbon fiber fabric	5.8	4.74	2	90						
note	_A preliminary analysis to the touch showed surface roughness. We replace baking paper with Teflon sheets for the detachment from the press. _Then visual analysis and analysis to the touch show more regular and uniform surfaces.											
S2C1_0.2_120	2 sheets of SEBS 0.17 mm	1 sheet of carbon fiber fabric	5.28	3.2	0.2	60						
S2C1_0.5_120			5.25	3.44	0.5	120						
S2C1_1_120			5.4	3.3	1	60						
S2C1_1_120			5.2	3.45	1	120						
S2C1_4_120			5.4	3.45	4	120						
S2C1_5_120			5.6	3.38	5	120	0.58	0.58	0.63	0.61	0.61	0.60
note	_At a pressure of 5 MPa, a more uniform distribution of SEBS is obtained.											

Table 2. SEBS–Biotex composite.

Specimen	Layer		Weight (g)		Pressure (MPa)	Time of Pressure (s)	Thickness (mm)					Medium Thickness (mm)
	Matrix	Reinforcement	Matrix	Reinforcement								
S4B1_1	4 sheets of SEBS 0.5 mm	1 sheet of Biotex	x	x	1	x	2.25	2.18	2.22	2.30	2.17	2.22
S4B1_2			x	x	2	x	2.05	2.12	1.74	1.89	1.92	1.94
S4B1_3			x	x	3	x	2.18	2.14	2.00	2.15	2.07	2.11
S4B1_4			x	x	4	x	1.73	1.89	1.87	2.18	2.24	1.98
note	_For a better control of the composite it is appropriate to record the weights of the materials before thermoforming them. _Minimize the thickness to optimize the performance of the material: more reinforcement and less matrix.											
S2B1_2_60	2 sheet of SEBS 0.17 mm	1 sheet of Biotex	4.54	5.4	2	60	0.78	0.74	0.73	0.70	0.78	0.75
note	_A preliminary analysis to the touch showed surface roughness. To ensure a better separation from the press machine. we replace baking paper with Teflon sheets. _Then visual analysis and analysis to the touch show more regular and uniform surfaces.											
S2B1_2_60	2 sheet of SEBS 0.17 mm	1 sheet of Biotex	4.62	5.8	2	60	0.77	0.77	0.75	0.78	0.77	0.77
S2B1_1_90			4.69	5.3	1	90	0.77	0.76	0.75	0.71	0.77	0.75
S2B1_0.5_120			4.71	5.58	0.5	120	0.98	1.08	0.99			1.02
note	_The visual analysis shows a non-uniform distribution of the SEBS with many air bubbles that may be related to the presence of water in the fabric. _As a possible solution we have ironed the fabric in the press at 180 °C for 90 s at 2 MPa. pressed slowly to not move the fibers.											
S2B1D_0.5_120	2 sheet of SEBS 0.17 mm	1 sheet of Biotex	5.54	6.25	0.5	120	0.92	1.04	0.98			0.98
note	_The visual analysis of the sample shows the absence of air bubbles. _The sample exceeds the visual and tactile analysis and it is subjected to Cross section analysis: good matrix-reinforcement interface.											

The materials obtained (Figure 9), which passed the analyses described in the "Methods" section (visual, tactile, cross-section), had the parameters described in Table 3.

Table 3. Final composite production parameters.

	Layer		Dimensions (mm)	Weight (g)		Pressure (MPa)	Time of Pressure (s)	Thickness (mm)		Medium Thickness (mm)
	Matrix	**Reinf.**		**Matrix**	**Reinf.**			**Matrix**	**Reinf.**	
SEBS–Carbon fiber fabric	2 sheets	1 sheet	70 × 200	5.35	3.40	5.0	120	0.170	0.290 ± 0.44	0.600
SEBS–Biotex	2 sheets	1 sheet	70 × 200	5.35	6.30	0.5	120	0.170	0.450–0.800	0.980

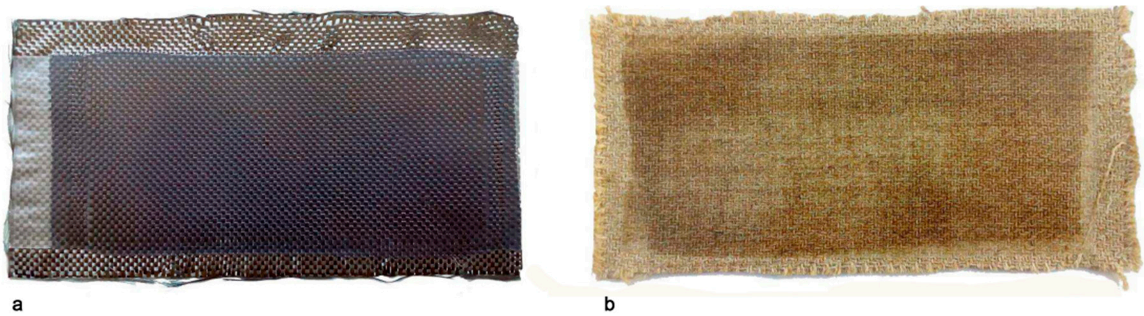


Figure 9. (**a**) SEBS–Carbon fiber fabric composite; (**b**) SEBS–Biotex composite.

For the SEBS–Biotex composite, it was necessary to remove water from the tissue, because its evaporation during thermoforming caused the formation of bubbles in the final composite. Flax fabric was therefore placed in the press at 180 °C at 2 MPa for 90 s, before the thermoforming process with the SEBS.

The surface finish of the composite was optimized by using a Teflon sheet as a surface for the detachment from the press. Thanks to this procedure, the SEBS surface remained transparent, leaving the texture of the underlying tissue visible.

4.2. Creation of Folding Pattern

The non-standard manufacturing process of the mold required the verification of feasibility using some samples as testers. Therefore, three cubic samples were made, of 20 × 200 × 2 mm^3 size with different thicknesses (300, 600, 900 mm). Then, the specimens were pressed to verify their behavior at 140 °C and put in contact with each other to fold them. The 300-mm-thick specimens broke at their edges, while the 600 mm and 900 mm ones successfully passed the test. Therefore, we decided to use the 600 mm thickness for the subsequent tests, because the 900-mm-thick specimen transferred the heat to the composite less evenly. For an initial verification of the possibility of creating a material-bending tessellation with the proposed system, it was applied to a simple system (i.e., an accordion-folded surface).

The two parts of the mold were placed in the press with the composite interposed. The temperature was set at 140 °C and the mold was not put under pressure, but only left in simple contact for 10 s. The composite reached the desired configuration, thus acquiring the possibility of kinematic movement and, at the same time, good resistance due to its shape (Figure 10). The angle between the faces of the mold used for this test was 90°.

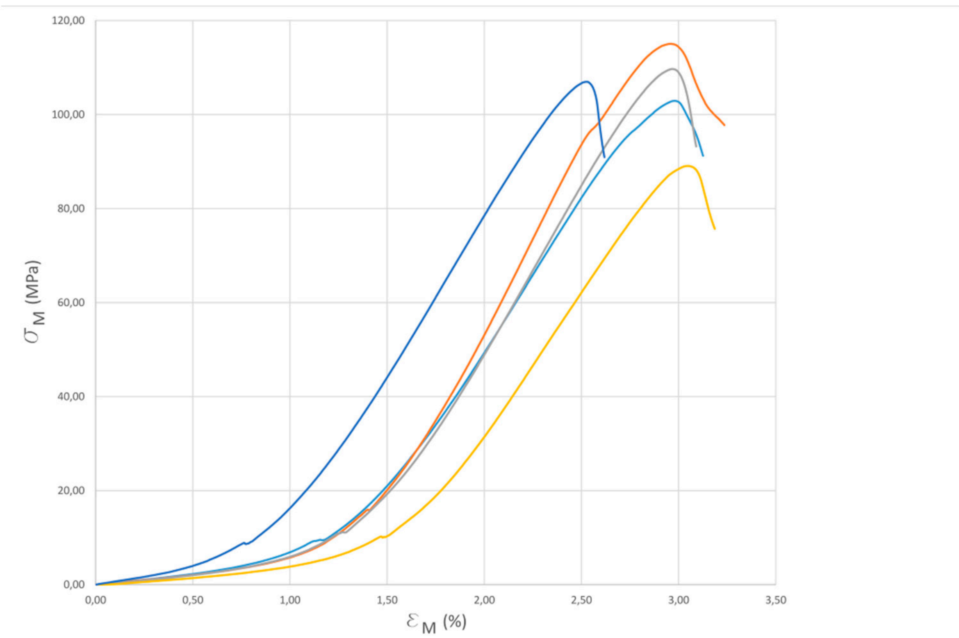
a b c

Figure 10. (**a**) Rapid prototyped mold for accordion-folded surface; (**b**) SEBS–Carbon fiber fabric folded composite; (**c**) SEBS–Biotex folded composite.

4.3. Mechanical Characterization

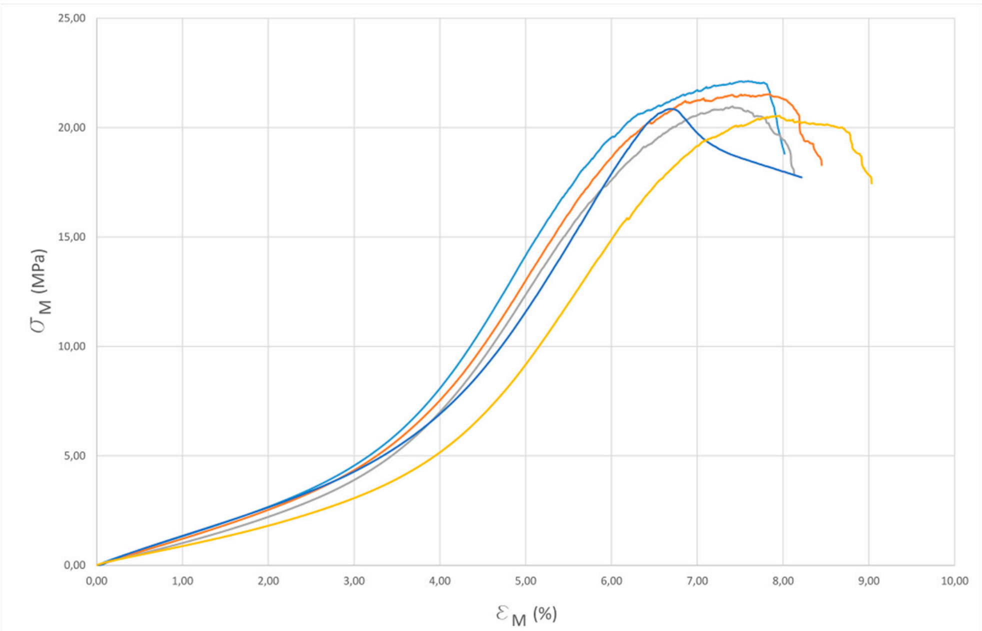
The uniaxial tensile tests on SEBS–Carbon fiber fabric samples showed stress–strain diagrams (Figure 11) with average tensile strength values of F_M = 1720 N, maximum stress σ_M = 104.73 N/mm^2, with standard deviation s = 9.81 N/mm^2, and coefficient of variation ν = 9.36. The mean deformation was ε_M = 2.9%, with standard deviation s = 0.2% and coefficient of variation ν = 7.27.

The uniaxial tensile tests of the SEBS–Biotex composite showed stress–strain diagrams (Figure 12) with average tensile strength values F_M = 521 N, maximum stress σ_M = 21.20 N/mm^2, with standard deviation s = 0.63 N/mm^2 and coefficient of variation ν = 2.96. The deformation ε_M had, in percentage, a mean value equal to 7.5%, with standard deviation s = 0.5% and coefficient of variation ν = 6.71.



Legends	Nr	a mm	b mm	A0 mm²	σY N	FM N	σM N/mm²	εM %	εB %	WB Nmm
	1	0,65	25	17,50	1800	1800	**102,90**	3,0	9,0	9366,47
	2	0,55	25	13,75	1580	1580	**115,04**	3,0	6,8	6672,40
	3	0,66	25	16,50	1810	1810	**109,68**	3,0	6,5	6616,03
	4	0,7	25	17,50	1560	1560	**89,06**	3,0	9,6	9811,18
	5	0,69	25	17,25	1850	1850	**106,96**	2,5	6,6	7023,26

Figure 11. Uniaxial tensile tests of the SEBS–Carbon fiber fabric composite.



Legends	Nr	a mm	b mm	A_0 mm²	σ_Y N	F_M N	σ_M N/mm²	ε_M %	ε_B %	W_B Nmm
	1	0.95	25	23.75	526	526	**22.13**	7.6	8.0	2964.66
	2	0.97	25	24.25	522	522	**21.53**	7.8	8.4	3211.85
	3	1.02	25	25.50	535	535	**20.97**	7.4	8.1	2963.97
	4	1	25	25.00	514	514	**20.54**	8.0	9.0	3178.65
	5	0.98	25	24.50	511	511	**20.86**	6.7	8.2	2857.29

Figure 12. Uniaxial tensile tests of the SEBS–Biotex composite.

Young's modulus (E) was calculated starting from the results of the uniaxial tensile tests with fibers arranged in parallel to the traction axis. Graphically, the linear section of the diagrams of each sample from which to determine this parameter was identified. Hook's law is valid in a linear elastic regime; therefore:

$$E = \sigma/\varepsilon.$$

Tables 4 and 5 report the Young's modulus of the SEBS–Carbon fiber fabric and SEBS-Biotex specimens and the mean Young's modulus (E_M) of each composite.

Table 4. Young's moduli of SEBS–Carbon fiber fabric specimens.

Specimen No.	E (MPa)
1	134.3
2	132.3
3	119.5
4	93.1
5	130.3
E_M	129.1

Table 5. SEBS-Biotex Young modulus. The value associated with specimen no. 4 was rejected due to excessive average deviation.

Specimen No.	E (MPa)
1	134.3
2	132.3
3	119.5
4	93.1
5	130.3
E_M	129.1

The load elongation curve of the samples subjected to bias extension was recorded (Figures 13 and 14) and, in order to obtain information on the shear stiffness, it was necessary to process the data from the testing apparatus. With the normalization methods proposed by Cuomo, Dell'Isola, and Greco for interpreting the data, it was possible to obtain the shear modulus G. This method [30] considers an in-plane balanced composite made of two orthogonal families of woven fibers, with the assumption that the composite has a constant thickness. Thus, the material can be treated as an equivalent 2D continuum, the fibers are inextensible, and the material deforms elastically.

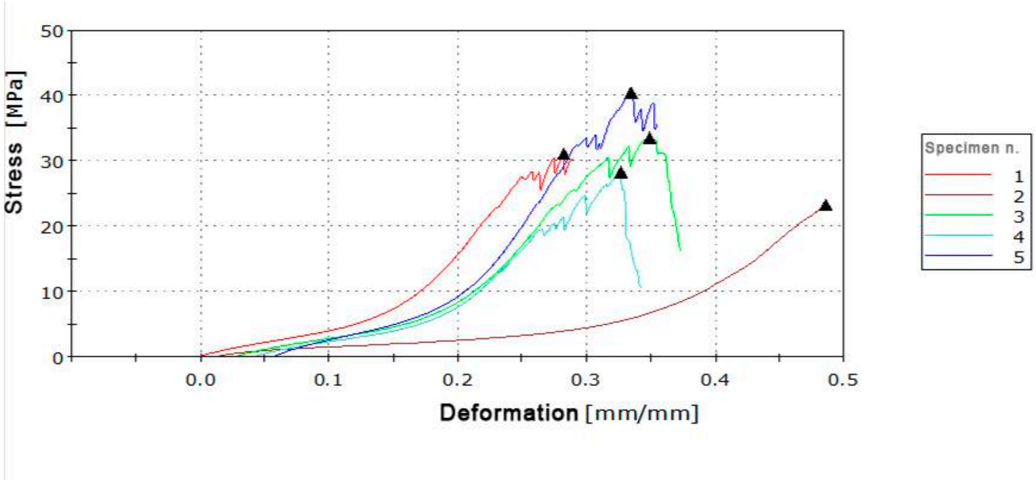


Figure 13. Biaxial extension tests of the SEBS–Carbon fiber fabric composite.

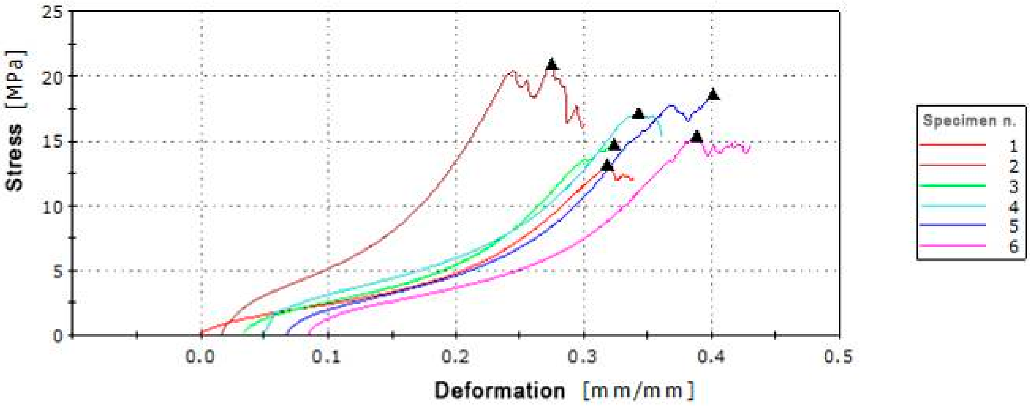


Figure 14. Biaxial extension tests of the SEBS–Biotex composites.

The results are showed in Tables 6 and 7. They report the shear modulus of the SEBS–Carbon fiber fabric and SEBS-Biotex specimens and the mean shear modulus (GM) of each composite.

Table 6. SEBS–Carbon fiber fabric shear modulus.

Specimen No.	G (MPa)
1	5.6
2	—
3	4.8
4	4.7
5	7.4
G_M	5.6

Table 7. SEBS–Biotex shear modulus.

Specimen No.	G (MPa)
1	3.2
2	—
3	3.8
4	4.3
5	4.2
6	3.5
G_M	3.8

For the SEBS–Carbon fiber fabric composite, once the value associated with specimen no. 2 was discarded, the mean value of G_M = 5.6 MPa was obtained.

For the SEBS–Biotex composite, the value associated with specimen no. 2 was discarded, so the mean value of specimens 1, 3, 4, and 5 and 6 was G_M = 3.8 MPa.

5. Discussion

The tests carried out on the new materials provided indications of the possibility of using textile composites with thermoplastic elastomer matrices for building envelopes. This use can have several implications on the sustainability of the building envelope, as better explained below.

The analysis carried out for the definition of the production parameters made it possible to obtain materials with a complete interpenetration between matrix and reinforcement, without macroscopic production problems or the formation of air bubbles.

The identification of a secondary production process for the realization of a folding pattern demonstrated the real advantage of using a thermoplastic matrix to create a pre-folded surface configurable according to the specific project.

Finally, after having proved the real possibility of making a pre-foldable textile composite with a thermoplastic elastomer matrix, mechanical characterization was used to prove the effective applicability of the material for the intended purposes. In particular, it was decided to compare the maximum stress of the new materials with those of the most common composites used for building components.

Table 8 [31] shows that SEBS–Biotex composite had similar properties to cotton textile blended with polyester, but it had a high weight; SEBS–Carbon fiber fabric had comparable properties with PTFE–fiber glass fabric, but it had a lower weight.

Table 8. Mechanical properties of new and commonly used composite materials for building components. PTFE: polytetrafluoroethylene.

Composite	Maximum Stress	Weight
Cotton/polyester blend	1000–2500 N/50 mm	350–520 g/m^2
SEBS–Biotex	21.20 N/mm^2 (≈1000 N/50 mm)	720 g/m^2
PTFE–Fiber glass fabric	3500–8000 N/50 mm	800–1500 g/m^2
SEBS–Carbon fiber fabric	104.73 N/mm^2 (≈3100 N/50 mm)	550 g/m^2

These results confirm that is possible to use these new materials for textile building envelopes and in particular for building adaptive envelopes. This type of component allows controlling indoor thermal conditions by regulating the passive operation of the building (e.g., incident solar radiation control or increase in natural ventilation by adapting the geometry to the prevailing wind). Such solutions have large convenience in building energy sustainability [32–34].

In particular, the solution proposed by the authors uses a thermoplastic elastomeric matrix to make the adaptive envelope, leading to important increases in terms of the sustainability.

Compared to traditional thermosetting composites, the following properties of this new material increase the economic and environmental sustainability of the envelope, due to:

1) Better recyclability;
2) Reduction of used materials;
3) Reduction of number of parts and of complexity;
4) Reduction of maintenance frequency.

As to the first point, because of its ability to be re-shaped upon heating, a thermoplastic matrix composite has a more rapid processing cycle and better recyclability compared to the thermoset matrix composites. Thermoplastic matrix composites can be recycled directly and easily by remelting and remoulding their constituents [35].

As to the second point, this type of envelope enables a lightweight load-bearing structure. In fact, the thermoplastic properties of the matrix make it possible to provide a pre-bending of the material, as shown in the "Creation of Folding Pattern" paragraph, which allows gives the surface resistance by shape [14].

The strong reduction in the number of parts and complexity of the components are due to the elastomeric properties of the matrix. Because the motion is achieved through the flexibility of its members and the material-wide elastic deformations, rather than through a link of multiple rigid parts together, the kinematics of the component involves a decreased assembly time and a simplified manufacturing processes. This allows also for a significant cost reduction to accomplish a specific performance.

Finally, they have few or no revolute or sliding joints. These conventional hinges require frequent maintenance cycles and can rust quickly. By using flexible material, these components' maintenance is much cheaper and less frequent, and there are no mechanical drawbacks such as backlash, vibration, and noise that would normally be caused by the friction in the hinges [36].

6. Conclusions and Future Work

The aesthetic characteristics and mechanical properties of the novel composite materials open the door to wide possibilities for the use of thermoplastic elastomers as coatings for textile architecture, in replacement of the most commonly used thermosetting polymers in building components; their kinematic mechanism introduces significantly simplified connections (no hinges) among the different tiles, resulting in considerable savings in component maintenance costs.

Potential applications have already been identified in other studies [37].

The future steps of this research will focus on the evaluation of the mechanical behavior of the folded surface. Among the methods proposed in the literature for the mechanical modeling of origami, the one adopted by Schenk is based on the modeling of the partially folded surface as a reticular structure. For this modeling method [38], it is fundamental to know the material stiffness matrix (K) and, especially, the dimensionless K_{facet}, K_{fold}, and K_{ratio} (= K_{facet}/K_{fold}) parameters that describe the properties of the material with which the origami model is made. It is therefore of primary importance to carry out tests to evaluate these parameters experimentally, and then proceed with the mechanical modeling of the various types of patterns applicable to the surface.

The research will also focus on the industrialization of the manufacturing process and on the evaluation of the most suitable methods for creating joints in the material to permit the connection of multiple sheets, and for connecting the composite to the substructure.

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